PLIOCENE TO RECENT STRATIGRAPHY OF THE CUU LONG AND NAM CON SON BASINS, OFFSHORE VIETNAM

A Thesis

by

CHRISTOPHER NEIL YARBROUGH

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2006

Major Subject: Geology

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Approved by:

Chair of Committee,	Steven L. Dorobek
Committee Members,	Brian J. Willis
	Niall Slowey
Head of Department,	Richard L. Carlson

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ABSTRACT

Pliocene to Recent Stratigraphy of the Cuu Long and Nam Con Son Basins, Offshore Vietnam. (May 2006)

Christopher Neil Yarbrough, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Steven L. Dorobek

The Cuu Long and Nam Con Basins, offshore Vietnam, contain sediment dispersal systems, from up-dip fluvial environments to down-dip deep-water slope and basinal environments that operated along the southern continental margin of Vietnam during Pliocene to Recent time. The available data enabled sediment thickness patterns, sequence-stratigraphic relationships, and channel types (fluvial to deep-water channels) within the lower Pliocene to Recent stratigraphic succession in the Cuu Long and Nam Con Son basins of offshore Vietnam to be analyzed. At least nine sequences and their accompanying systems tracts exist in the Pliocene to Recent section. Shelf-edge development in the study area is limited to the Eastern Nam Con Son Sub-Basin. Overall south to southeastward migration of the shelf edge complex during Pliocene to Recent time indicates that the Paleo-Mekong River System was the dominant sediment source for the area.

ACKNOWLEDGEMENTS

My sincere appreciation goes to Dr. Steven Dorobek for taking me on as his graduate student. His guidance was an invaluable asset in the molding of my ideas during research and completion of this paper. I would also like to thank my other committee members Dr. Brian Willis and Dr. Niall Slowey. All of my committee members provided a strong and encouraging academic environment that helped me tremendously.

Halliburton Geophysical Services generously provided Texas A&M University access to the data set that was the foundation of this study. The financial support of the AAPG Grants in Aid, and the Texas A&M Department of Geology and Geophysics T.A. programs helped me pursue my graduate career.

This project would not have been possible without the assistance of Khryste Wright. She got me through times when the data seemed to be overwhelming or too hard to interpret. Many other friends, too many to mention here, made my time at Texas A&M a truly great experience.

Most importantly, I would like to thank God, my family back home in Fort Stockton, and my wife Catherine. Their love and support got me through the many long nights of research.

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CHAPTER I

INTRODUCTION

The available data provided a unique opportunity to map sediment dispersal systems, from up-dip fluvial environments to down-dip deep-water slope and basinal environments that operated along the southern continental margin of Vietnam (Figure 1) during Pliocene to Recent time.

The stratigraphic framework constructed during this study is shown to be related to eustatic sea-level change, differential subsidence across the study area, and sediment flux from various continental source areas in Asia. Sediment thickness patterns, sequence-stratigraphic relationships, and channel types (fluvial to deep-water channels) within the lower Pliocene to Recent stratigraphic succession in the Cuu Long and Nam Con Son basins of offshore Vietnam were analyzed in this study. Transitions from fluvial-deltaic to deep-marine sediment dispersal systems across offshore Vietnam throughout Pliocene to Recent time were mapped.

The Mekong River has been the main sediment source for the Cuu Long and Nam Con Son basins of offshore Vietnam since middle Miocene time (Murray and Dorobek, 2004). Headwaters of the Mekong River originate in the highlands of eastern Tibet near

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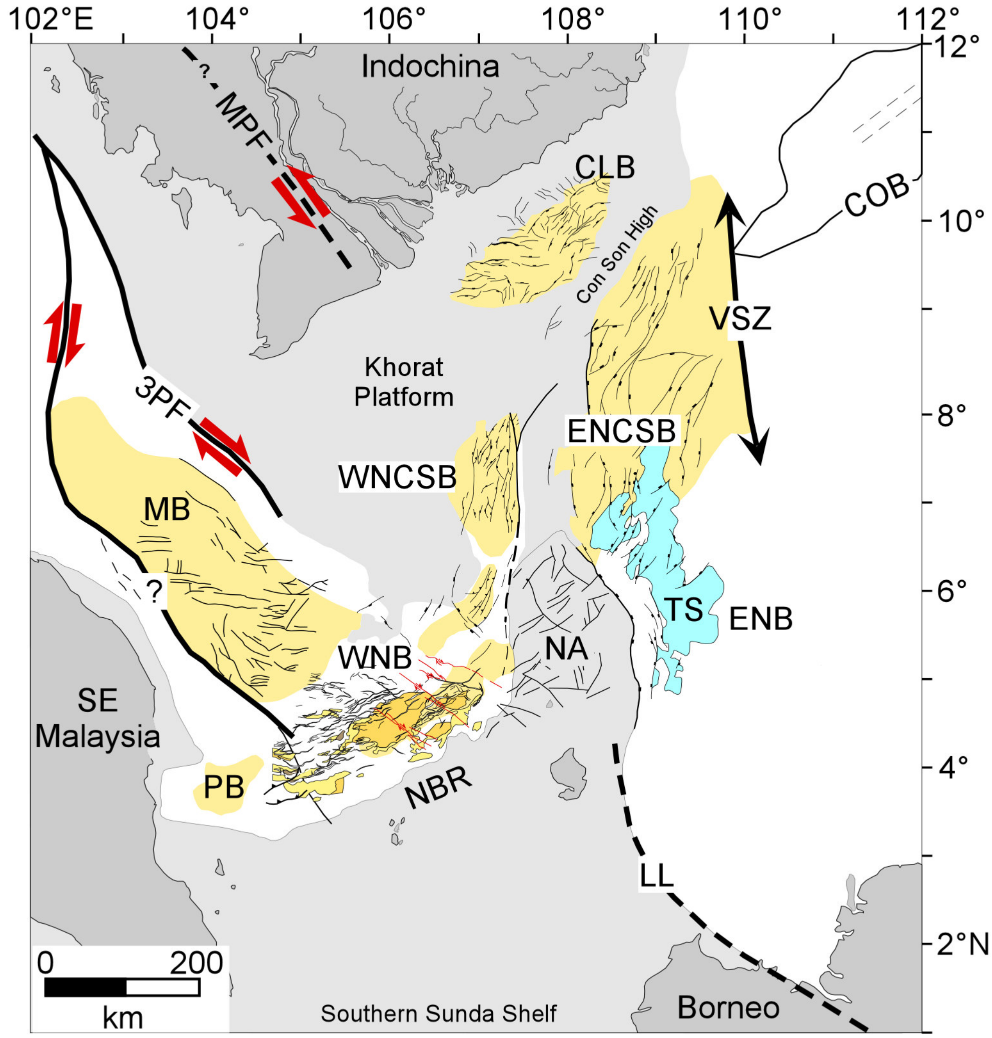

Figure (1). Regional tectonic map of Southeast Asia (modified from Murray, 2003). The areas examined during this study include the Khorat Platform, Cuu Long Basin (CLB), Western Nam Con Son Basin (WNCSB), and Eastern Nam Con Son Basin (ENCSB). Other tectonic features and basins include the continental ocean boundary (COB), Natuna Arch (NA), Natuna Basement Ridge (NBR), West Natuna Basin (WNB), East Natuna Basin (ENB), Lupar Line (LL), Malay Basin (MB), Mai Ping Fault (MPF), Three Pagodas Fault (3PF), Terumbu Shelf (TS), and Vietnam Shear Zone (VSZ).

Dzanag La Pass in the Tanghla Shan mountain ranges at an elevation of ~5,000 meters (Ta et al., 2002).

Neogene dispersal patterns in the Cuu Long and Nam Con Son basins have been analyzed by Murray (2003), but at a much coarser scale than this study. The Neogene stratigraphy of the study area provides information about tectonic uplift along the eastern flank of the Tibetan Plateau, and the evolution of the East Asian Monsoon, one of the most important annual climatic cycles on Earth.

CHAPTER II

METHODS

Stratigraphic and structural interpretations completed in this study were based on a 1969-1970 Ray Geophysical survey reprocessed in 1989-1990 by Halliburton Geophysical Services, Inc. (HGS) from offshore Vietnam (Figure 2). The survey consists of 2-D seismic-reflection data on twenty-six individual lines totaling >1000 km in length. The profiles consist of 5.0 seconds (TWT) of migrated seismic data. The complete 1989 HGS survey also covered areas of offshore southern Cambodia, in the southern South China Sea, but these data were not included in this study. Large tectonic elements covered by the survey include the Cuu Long Basin, Khorat Platform, Eastern Nam Con Son Sub-Basin, and Western Nam Con Son Sub-Basin (Figure 1). All of the seismic sections used consisted of paper data; no digital data were available.

Six proprietary wells from the southern South China Sea region were used to constrain lithologies and chronostratigraphic relationships across the study area. The well data include information on biostratigraphy, lithology, chronostratigraphic boundaries, seismic velocities, and formation-top picks. Key chronostratigraphic boundaries and formation tops recognized in the well data were tied to seismic sections using available seismic-velocity information. Most wells are located over 10 km from any given seismic line, so that horizon picks had to be projected onto the nearest seismic line. For wells that did not contain velocity data, depths to key chronostratigraphic horizons were based on estimated seismic velocities.

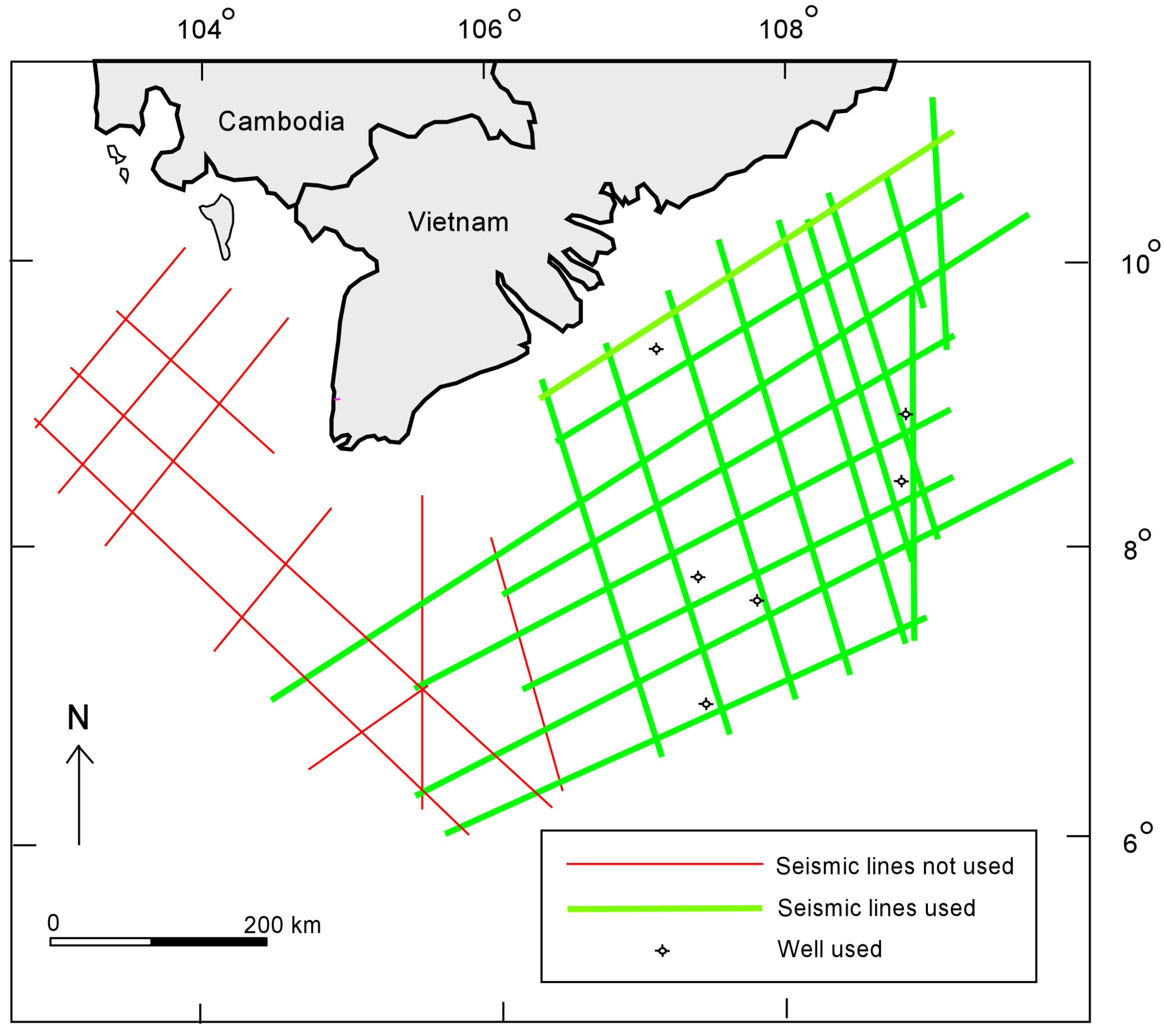

Figure (2). Location of seismic lines in the HGS survey, and petroleum exploration wells used in this study. Green lines indicate lines used in this study, whereas red lines indicate lines not used.

Analysis of seismic-reflection termination patterns (e.g., onlap, downlap, and erosional truncation) and seismic characteristics (e.g., amplitude and lateral continuity) aided in characterizing major tectonostratigraphic boundaries and in construction of a sequence stratigraphic framework for the Pliocene to Recent succession across the study area. Previous studies that have analyzed major stratigraphic boundaries in the South China Sea (Mathews and Todd, 1993; Mathews et al., 1997; Lee et al., 2001; Olson, 2001; Murray, 2003) also helped to constrain interpretation of the data set used in this study.

Horizons picked in the HGS survey included; 1) top of pre-Tertiary basement, 2) top of Eocene(?)-lower Oligocene syn-rift strata, 3) top of middle-upper Oligocene, 4) top of lower Miocene, 5) top of middle Miocene (middle Miocene unconformity), 6) top of upper Miocene (upper Miocene unconformity), and 7) top of early Pliocene. The middle Miocene unconformity (MMU) and upper Miocene unconformity (UMU) are key tectonostratigraphic surfaces that are recognized in basins across the Sunda Shelf and served as important reference horizons for regional stratigraphic correlations, especially where there was little well control.

Seismic facies were also characterized within the Pliocene to Recent interval and provided insight into the long-term evolution of depositional systems across the study area. Recognition of specific seismic facies (e.g., clinoform facies, fluvial incision features, submarine fans) also helped guide sequence stratigraphic interpretations.

Maps created from the HGS survey enabled analysis of the Cuu Long and Nam Con Son Basins. Various isochron, and paleogeographic maps for Pliocene to Recent time were created. Spacing of the seismic lines in the HGS survey is large. All isochron maps, and paleogeographic maps should be interpreted as first-order due to spacing of the data.

CHAPTER III

TECTONIC FEATURES AND BASINS OF THE STUDY AREA

Khorat Platform Location and Stratigraphy

The Khorat Platform is a shallow basement high that extends offshore from the southern part of the Indochina Peninsula and is composed of pre-Tertiary metamorphic and intrusive igneous rocks (Figure 1). Sedimentary cover over the Khorat Platform is thin (<1.5 seconds TWT), and for the most part undeformed . The oldest strata, except for local Paleogene syn-rift fill in small half-grabens, consist of the middle Miocene Arang Formation, which unconformably overlies pre-Tertiary basement rocks and consists of sub-parallel seismic facies. Younger stratigraphic units have not been formally named and little is known about their stratigraphic relationships or lithofacies.

Cuu Long Basin Location and Stratigraphy

The Cuu Long Basin is located directly offshore of the present-day Mekong River Delta (Figure 1). The Cuu Long Basin formed during Eocene(?)-Oligocene rifting that affected much of the continental crust that underlies the southern South China Sea (Figure 3). Rifting continued until Oligocene time. From early Miocene to Recent time, the Cuu Long Basin has undergone gentle thermal subsidence (Olson, 2001). There is only minor evidence within the Cuu Long Basin of the post-rift inversion events that have affected many other rift basins of the southern South China Sea and Indonesian back-arc region (Olson, 2001).

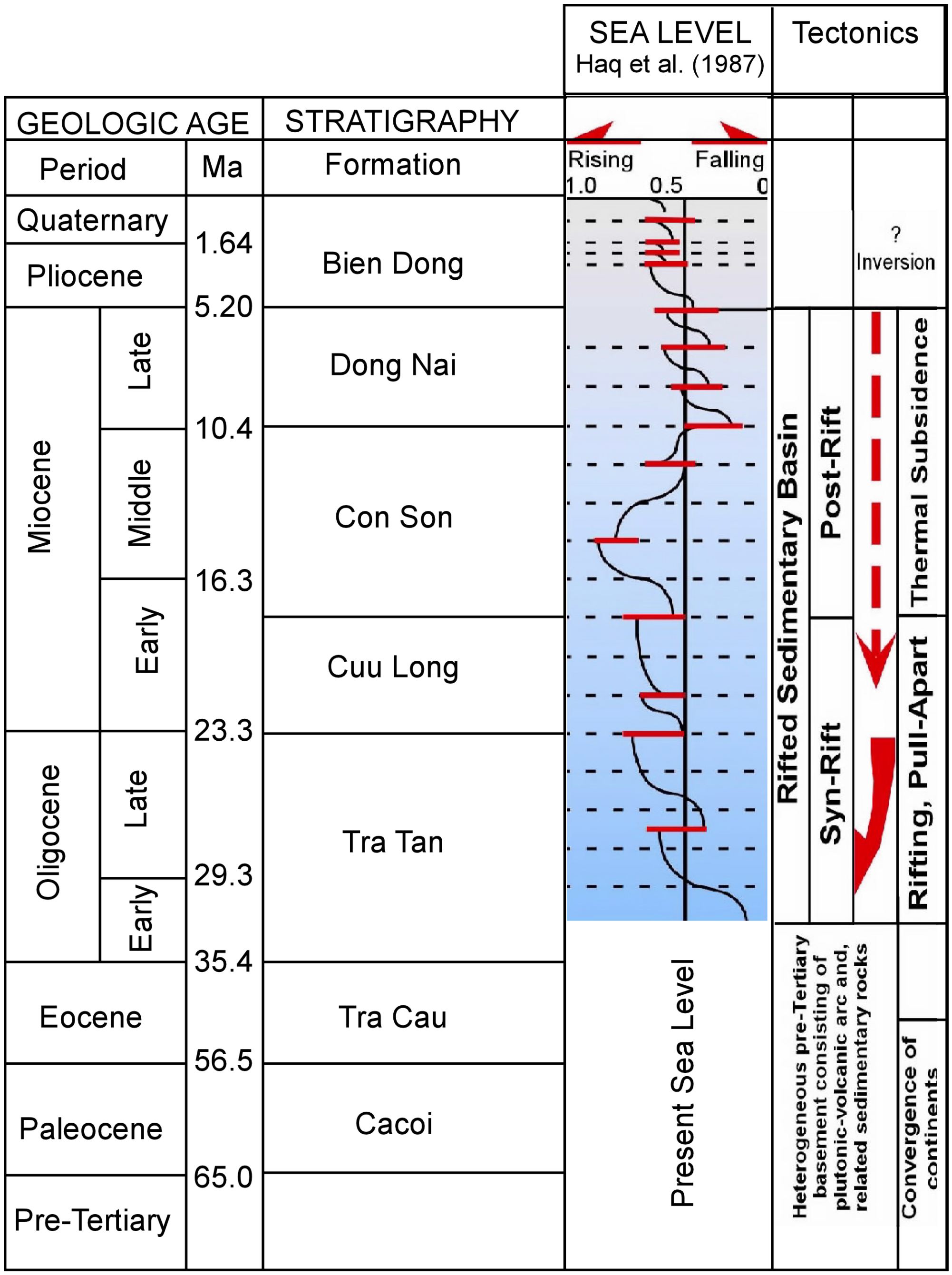

Figure (3). Stratigraphy chart for the Cuu Long Basin (Modified from Olson, 2001). Chart illustrates lithostratigraphic, chronostratigraphic, tectonostratigraphic, petroleum systems, and key tectonic and eustatic events. Eustatic sea-level curves from Haq et al. (1987).

The Cuu Long Basin has seven lithostratigraphic units that overlie pre-Tertiary basement (Figure 3). These units include: (1) syn-rift deposits of the Eocene(?) Ca Coi Formation, (2) Eocene(?)-Oligocene Tra Cau Formation, and (3) upper Oligocene Tra Tan Formation; and post-rift deposits of the (4) lower Miocene Bach Ho Formation, (5) middle Miocene Con Son Formation, (6) upper Miocene Dong Nai Formation, and (7) Pliocene to Recent Bien Dong Formation.

Until Miocene time, the main sediment source for the Cuu Long Basin was local footwall highs of rifted fault blocks. From Miocene to Recent time, however, the main sediment source area likely changed to mainland SE Asia, based on the south to southeastward prograding clinoforms that filled the basin. The Mekong River has been the main supplier of sediment to the Cuu Long Basin since Miocene time (Murray and Dorobek, 2004). The Cuu Long Basin lacks any substantial carbonate buildups because of its proximity to the Mekong River Delta and little post-rift thermal subsidence (Olson, 2001).

Cuu Long Basin Lithofacies

Pre-Tertiary Basement

Basement rocks in the Cuu Long Basin are composed of Cretaceous granites, andesites, rhyolites, and granodiorites with ages of 178 Ma and 108 Ma (San et al., 1993). These basement rocks formed as a volcanic arc system that extended from the eastern margin of Vietnam, southward through the Natuna Arch, and into south-central Borneo during Jurassic to Cretaceous time (San et al., 1993).

Eocene(?) to Oligocene Ca Coi Formation

The Eocene(?) to Oligocene Ca Coi Formation consists of boulder-conglomerate facies interbedded with mudstone horizons (Bat et al., 1993; San et al., 1993). In parts of the Cuu Long Basin, the Ca Coi Formation reaches a thickness of up to 1000 meters (Olson, 2001). Most of the boulder-conglomerate facies are composed of clasts from underlying pre-Tertiary basement (San et al., 1993).

Lower Oligocene Tra Cu Formation

The lower Oligocene Tra Cu Formation is composed of siltstones/siltstones, and fine to medium grained sandstone with thin interbedded coal beds. Approximately 60% of the formation is made up of mudstone and interbedded volcanic layers (San et al., 1993).

Upper Oligocene Tra Tan Formation

The upper Oligocene Tra Tan Formation consists of fine grained-arkosic sandstone that fines upwards to siltstone and claystone. The Tra Tan Formation is 400 to 800 meters thick. The Tra Tan Formation was deposited in fluvial-alluvial to lacustrine environments (Bat et al., 1993).

Lower Miocene Bach Ho Formation

The lower Miocene Bach Ho Formation is composed of siltstone and arkosic sandstones with thin interbeds of claystone. Marine depositional conditions in the Cuu Long Basin began with the deposition of the lower portion of the Bach Ho Formation.

Upper portions of the lower Miocene Bach Ho Formation contain a clay unit measuring up to 150 meters thick in some Cuu Long Basin Wells. The Back Ho Formation was largely deposited in delta, delta plain, and marginal marine environments (Bat et al., 1993; San et al., 1993).

Middle Miocene Con Son Formation

The middle Miocene Con Son Formation consists of a basal shale that grades upward to fine-grained sandstone with interbedded mudstone and local marl facies. The Con Son Formation is 800 to 1000 meters thick and was deposited in nearshore, shallow marine environments (Bat et al., 1993; San et al., 1993).

Upper Miocene Dong Nai Formation

The upper Miocene Dong Nai Formation is composed of coarse-grained arkosic sandstone with thin interbedded layers of gravel, claystone, and siltstone. The Dong Nai Formation ranges is 500 to 600 meters thick. The Dong Nai Formation was deposited in a deltaic environments (Bat et al., 1993; San et al., 1993).

Pliocene to Quaternary Bien Dong Formation

The Pliocene to Quaternary Bien Dong Formation consists of fine and coarse grained sandstone with interbeds of fossileferous mudstone. The Bien Dong Formation is 500 to 700 meters thick and was deposited in shallow-water, inner-shelf, to open marine, outer-shelf environments (Bat et al., 1993; San et al., 1993).

Nam Con Son Basin Location and Stratigraphy

The Nam Con Son Basin (Figure 1) experienced three phases of rifting from Paleogene to late Miocene time (Matthews et al., 1997). Like the Cuu Long Basin, the Nam Con Son Basin initially formed during Paleogene rifting events caused by the collision of India and Eurasia, followed by lesser amounts of extension related to southwestward propagation of seafloor spreading in the southwestern sub-basin of the South China Sea (Gerke, 1996; Murray and Dorobek, 2004). During middle Miocene time, the Nam Con Son Basin underwent local shortening and inversion (Tjia and Liew, 1996; Matthews et al., 1997; Olson, 2001). Olson (2001) divided the Nam Con Son Basin into two sub-basins: the Eastern and Western Nam Con Son Sub-Basins, which are separated by a northward-plunging, fault-bounded extension of the Natuna Arch to the South.

Strata that fill the Nam Con Son Basin consist of seven lithostratigraphic units that overlie pre-Tertiary basement (Figure 4). These units include: (1) an unnamed Eocene unit, (2) Oligocene Cau Formation, (3) lower Miocene Dua Formation, (4) middle Miocene Thong Formation, (5) middle Miocene Mang Cau Formation, (6) upper Miocene Nam Con Son Formation, and (7) Pliocene to Recent Bien Dong Formation (Matthews et al., 1997).

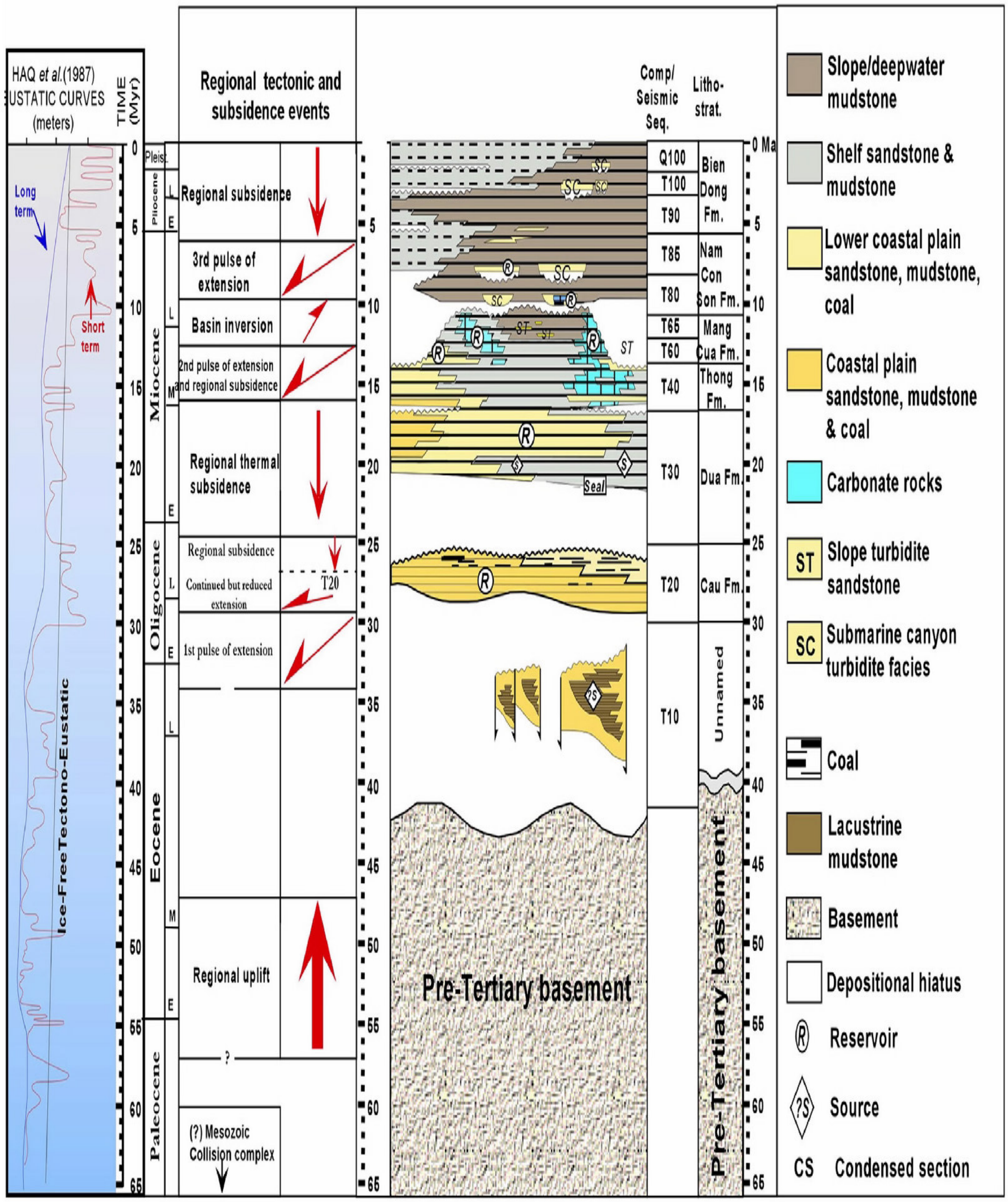

Figure (4). Nam Con Son Basin tectonostratigraphic summary (Modified from Olson, 2001). Tectonostratigraphic and lithostratigraphic information from Matthews et al.(1997). Eusatic sea-level curves from Haq et al.(1987).

Nam Con Son Basin Lithofacies

Pre-Tertiary Basement

The pre-Tertiary basement of the Nam Con Son Basin is similar to basement rocks of the Cuu Long Basin. Basement rocks of the Nam Con Son Basin are composed of Cretaceous granites (Olson, 2001).

Eocene(?) to Lower Oligocene

The Eocene(?) to lower Oligocene strata of the Nam Con Son Basin are not formally named and poorly understood. These strata consist of syn-rift conglomerate and coarse grained-sandstone that were deposited in a fluvial-lacustrine environments (Matthews et al., 1997).

Oligocene Cau Formation

The Oligocene Cau Formation is composed of coarse-grained quarztose sandstone with thin layers of coal, claystone, and siltstone that were deposited in fluvial-deltaic settings (Bat, 1993). The thickest parts of the Cau Formation were deposited in the Eastern Nam Con Son Sub-Basin (Matthews et al., 1997).

Lower Miocene Dua Formation

Que (1993) subdivided the lower Miocene Dua Formation into lower, middle, and upper intervals. The lower Dua Formation is made up of claystone with thin layers of sand and coal. The middle Dua Formation is composed of quartzose sandstone with thin layers of claystone. The upper Dua Formation is composed mainly of claystone with sparse thin sandstone layers. The Dua Formation is 700 to 900 meters thick. This unit was deposited during overall transgressive conditions, with the lower Dua Formation deposited in fluvial-deltaic environments, and a gradual transition to open marine shelf environments for the upper Dua Formation (Que, 1993).

Middle Miocene Thong Formation

The middle Miocene Thong Formation consists of poorly sorted sandstone with thin layers of calcareous claystone that become more common in the upper part of this unit (Bat et al., 1993). During middle Miocene time, eastern parts of the East Nam Con Son Sub-Basin began to subside at a greater rate than the western reaches of the East Nam Con Son Sub-Basin, so that the Thong Formation was deposited in marginal to non-marine environments in the west and more marine environments in the east (Matthews et al., 1997).

Middle Miocene Mang Cau Formation

Bat et al. (1993) divided the middle Miocene Mang Cau Formation into lower and upper units. The lower Mang Cau Formation is composed of sandstone and carbonate-rich claystone, whereas the upper Man Cau Formation consists of packstone and calcareous claystone, with thin sandstone layers (Bat, 1993). The prominent middle Miocene unconformity (MMU) lies at the top of the upper Mang Cau Formation (Matthews et al., 1997). The MMU formed during a major eustatic lowstand (Haq et al., 1987), although it was enhanced in the Nam Con Son Basin by tectonic uplift and inversion across southern and eastern portions of the basin (Olson, 2001).

Upper Miocene Nam Con Son Formation

Bat et al. (1993) and Que (1993) divide the upper Miocene Nam Con Son Formation into lower and upper units. The lower Nam Con Son Formation consists of calcareous mudstone, claystone, and thin layers of sandstone. The upper Nam Con Son Formation is mainly composed of limestone and is 500 to 1000 meters thick (Bat et al., 1993; Que, 1993). The Con Son Formation represents the main phase of middle Miocene carbonate sedimentation in the Nam Con Son Basin. The upper Miocene unconformity (UMU) lies at the top of the Nam Con Son Formation (Matthews et al., 1997).

Pliocene to Recent Bien Dong Formation

The Pliocene to Recent Bien Dong Formation is composed of mudstone, siltstone and sandy turbidite deposits (Bat et al., 1993). In the Nam Con Son Basin, the Bien Dong Formation is 500 to 700 meters thick. During Pliocene to Recent time, the paleo-Mekong River began to be the main sediment source for the Nam Con Son Basin (Murray and Dorobek, 2004). The paleo-Mekong River delta began to prograde quickly across the Con Son High and terminated much of the carbonate sedimentation within the Nam Con Son Basin (Matthews et al., 1997). This study largely focused on sequence stratigraphic relationships in the Bien Dong Formation.

CHAPTER IV

SEISMIC FACIES AND SEQUENCE STRATIGRAPHY

Concepts of seismic stratigraphy were described in a classic paper by Vail et al. (1977). Mitchum and Vail (1977) set forth methods of seismic stratigraphic analysis. Seismic termination patterns such as onlap, downlap, and toplap help constrain systems tract location and sequence identification. Seismic stratigraphy was soon merged with well and outcrop data, evolving into sequence stratigraphy (Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner et al., 1990).

Original models of sequence stratigraphy viewed formation of sequences at all stratigraphic levels as products of eustatic sea-level flucuations. Sequence stratigraphy has since switched emphasis from global sea-level changes to a more, “neutral curve of relative sea-level (base level) changes that can accommodate any balance between allogenic controls on accommodation” (Catuneanu, 2002).

Seismic Facies of the Study Area

Three seismic facies can be recognized within Pliocene to Recent strata across the study area: (1) channelized facies, (2) parallel to sub-parallel facies, and (3) clinoform wedge facies. Gas disturbed zones exist in the strata and obscure seismic facies and stratal patterns. Gas zones can mimic fluvial incision and must be analyzed with care.

Channelized Seismic Faces

Channelized seismic facies represent areas of incision in Pliocene to Recent strata. Channels across the Sunda Shelf region have been characterized and analyzed by Murray & Dorobek (2004). Channels within the study area are characterized by U-shaped geometries, lateral changes in amplitude, chaotic to conformable fill, and are interpreted to be fluvial in origin. Fluvial channel features are ~0.1 – 0.5 km wide and 0.05 – 0.1 seconds TWT deep. Broad areas of incision, interpreted to be fluvial incised valleys, also contain similar fill as fluvial channels, but are much larger in scale. Incised valleys are ~1 – 3 km wide and ~0.05 – 0.2 seconds TWT deep.

In lower Pliocene strata, channelized seismic facies are dominantly found along sequence boundaries (SB). In upper Pliocene to Recent strata, the abundance of channelized seismic facies increases, creating laterally discontinuous reflectors

Parallel to Sub-parallel Seismic Facies

Parallel to sub-parallel seismic facies are found in both inner shelf and basinal settings. In the study area, this seismic facies is characterized by laterally continuous, sub-horizontal to gently dipping reflectors.

Parallel to sub-parallel seismic facies that show strong lateral continuity and high amplitude are interpreted to be deposited in inner-shelf environments. Where this facies is found seaward of clinoform wedge facies, amplitudes are lower and lateral continuity decreases, and deposition occurred in basinal settings. Basinal parallel to sub-parallel seismic facies are only seen in the far eastern portions of the study area, where the greatest subsidence has occurred.

During times when base-level drops below the shelf offlap break, fluvial incision can occur updip, on the exposed shelf. Shelf settings with parallel to sub-parallel seismic facies also contain sharp to irregular zones of channelized seismic facies that formed during rapid base-level falls. Distinction between these two seismic facies is key to locating sequence boundaries in strata when the diagnostic clinoform wedge seismic facies is missing.

Clinoform Wedge Seismic Facies

Clinoform wedge seismic facies can be seen in areas of shelf-edge development in Pliocene to Recent strata across the study area. This seismic facies is characterized by reflections with medium to high continuity and low to high amplitude. Reflectors of this facies have dips of $> 1^{o}$. In the Nam Con Son Basin updip reflectors of this facies transition into parallel to sub-parallel shelf reflectors, whereas downdip, clinoform reflectors transition into basinal parallel to sub-parallel reflectors.

LST are bounded on the bottom by a sequence boundary and on the top by a transgressive surface. Internal reflectors of the LST downlap onto the underlying sequence boundary. After base level drop has occurred, slope and basin floor fans can be deposited. Strata of these fans display bi-directional downlap onto the underlying sequence boundary. Topset accommodation begins once the rate of base level drop has slowed enough to allow for incising river profiles to stabilize. Depending on the rates of sediment supply and creation of accommodation space, topset clinoforms of the LST can be either progradational or aggradational (Emery and Myers, 1996). LST reflectors within the study area exhibit progradational geometries.

TST are bounded on the bottom by the maximum regressive surface and at the top by the maximum flooding surface. Transgression of the shoreline occurs when base level rise is greater then sedimentation rates. This transgressive pattern results seismically in onlapping and backstepping reflectors on the underlying LST. TST within the study area are less then 0.20 seconds TWT thick and display diagnostic onlapping geometry. The shallow dip and large surface area of the Sunda Shelf caused TST strata of the Cuu Long Basin, Con Son Ridge, and Western Nam Con Son Sub-Basin to thin to less than 0.03 seconds TWT.

HST are bounded on the bottom by the maximum flooding surface and at the top by a sequence boundary. Once the rate of base level rise drops below sedimentation rates, normal regression of the shoreline occurs. Early highstand reflector geometries can be aggradational in nature, while mid to late highstand reflector geometries can become progradational. Vertical analysis of HST internal reflectors indicate loss of topset accommodation through time (Emery and Myers, 1996). Base level drop causes terminal HST reflectors to display toplap truncation at the overlying sequence boundary. HST of the study area exhibit all of these diagnostic reflector geometries.

Pliocene to Recent Sequence Stratigraphy

Seismic-stratigraphic relationships within the Pliocene to Recent strata across the study area show that at least nine, third-order, depositional sequences comprise this stratigraphic interval (Figure 5). Component systems tracts within each depositional sequence and the characteristics of sequence boundaries were identified and mapped (Figures 6 and 7) across the study area in order to reconstruct the paleogeographic

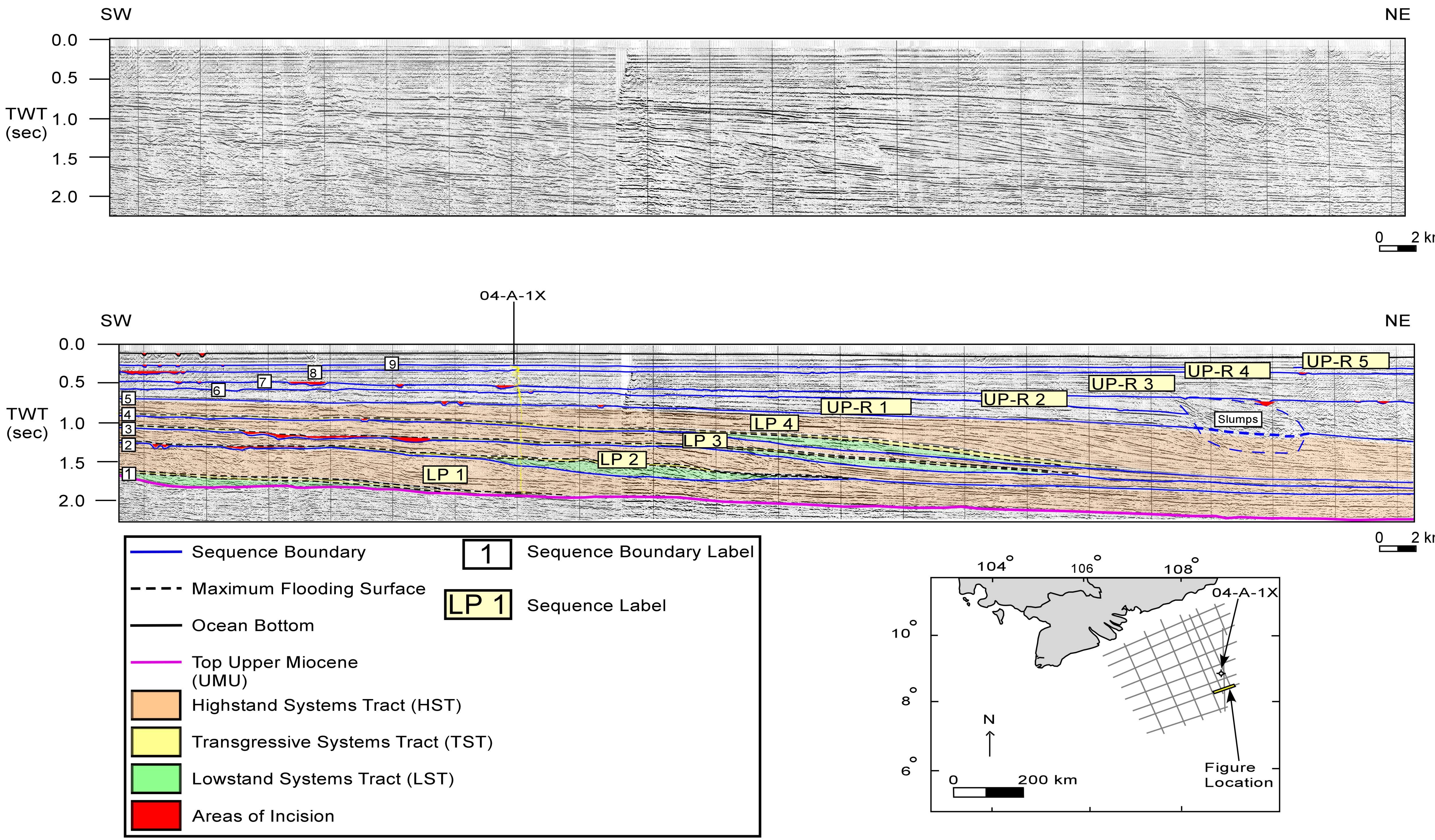

Figure (5). Pliocene to Recent seismic section. Diagnostic features, HST, LST, and TST shelf-edge stratal architecture is best observed in the Lower Pliocene section. Sequence boundaries in the Upper Pliocene to Recent strata are identified by fluvial incision features. The gamma ray well log is projected from ~50 km northwest in the ENCSB.

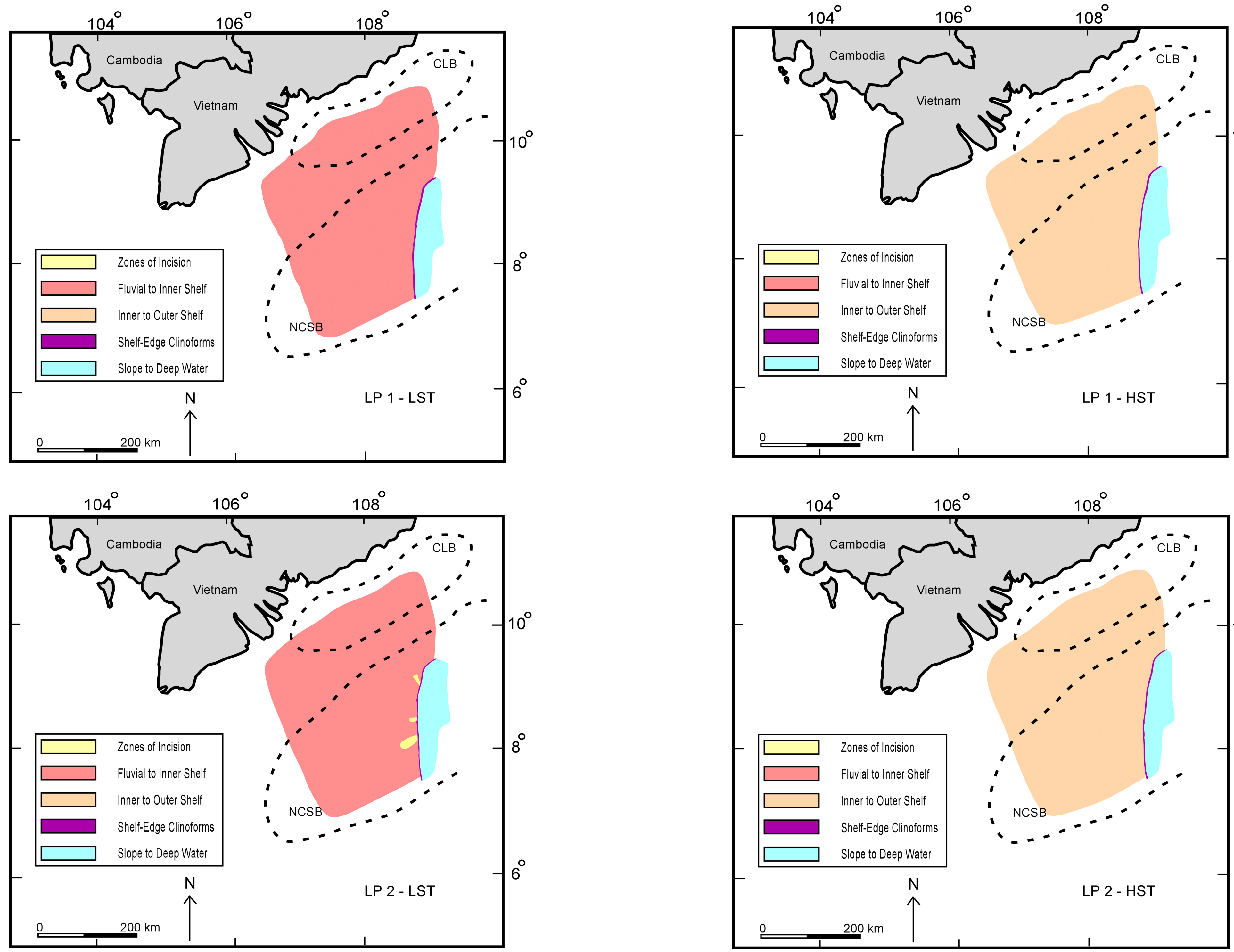

Figure (6). Paleogeographic interpretations for LP 1 and LP 2 terminal stage LST and HST deposition. Cuu Long (CLB) and Nam Con Son Basin (NCSB) boundaries are indicated by dashed lines. Division of the Nam Con Son Basin into East and West sub-basins is not shown.

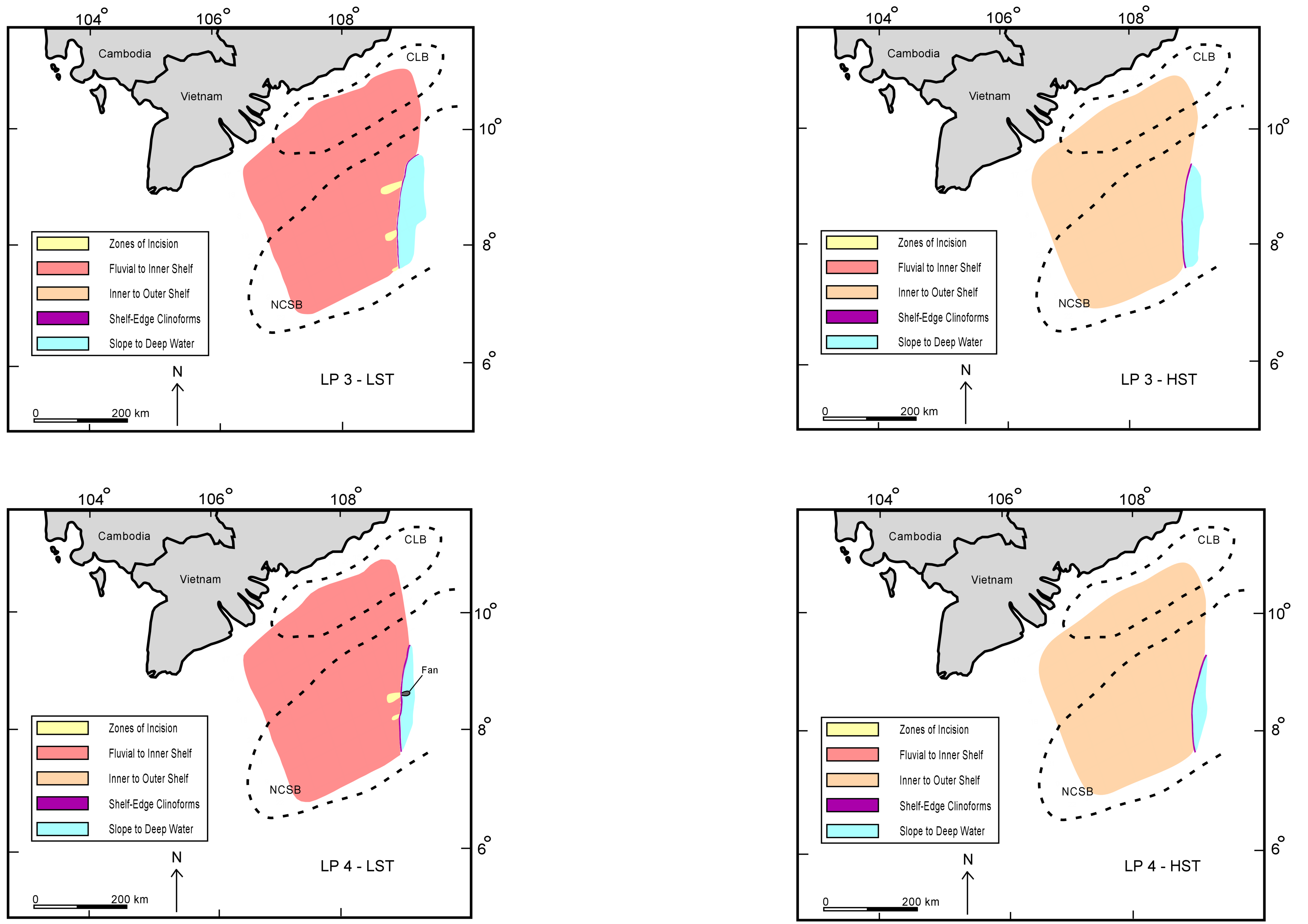

Figure (7). Paleogeographic interpretations for LP 3 and LP 4 terminal stage LST and HST deposition. Cuu Long (CLB) and Nam Con Son Basin (NCSB) boundaries are indicated by dashed lines. Division of the Nam Con Son Basin into East and West sub-basins is not shown.

evolution of offshore Vietnam during Pliocene to Recent time.

Overall, Pliocene to Recent strata across the study area record long-term, southeastward progradation of siliciclastic depositional systems. The dominant southeastward progradation direction indicates that the paleo-Mekong River System supplied the majority of sediment to offshore Vietnam during Pliocene to Recent time. Figures 6 and 7 represent paleogeographic interpretations for the terminal stages of the LST and HST of LP 1 through 4.

Lower Pliocene Sequence 1 (LP 1)

LP 1 (Figure 5) is defined by SB 1 at its base and SB 2 at its top. SB 1 is the UMU, a key tectonostratigraphic surface that is recognized throughout the study area and surrounding Sunda Shelf. SB B is identified by zones of fluvial incision westward of the LP 2 LST, and toplap truncation of the clinoforms in the underlying HST of LP 1. Fluvial incision features along SB 2 are ~0.1 – 0.5 km wide and 0.05-0.1 seconds TWT deep.

LP 1 is recognizable throughout the study area in both the Cuu Long and Nam Con Son Basins. In the Cuu Long Basin and over the Con Son Ridge, LP 1 is less than ~0.3 seconds TWT thick. In the Western Nam Con Son Sub-basin, Sequence I is ~0.3 – 0.4 seconds TWT thick. It thickens into the Eastern Nam Con Son Sub-basin where it attains its maximum thickness of ~0.6 seconds TWT, within progradational clinoform facies. LP 1 thins farther eastward to less than ~0.3 seconds TWT where clinoform facies transition into distal slope and basin-floor facies (Figure 8).

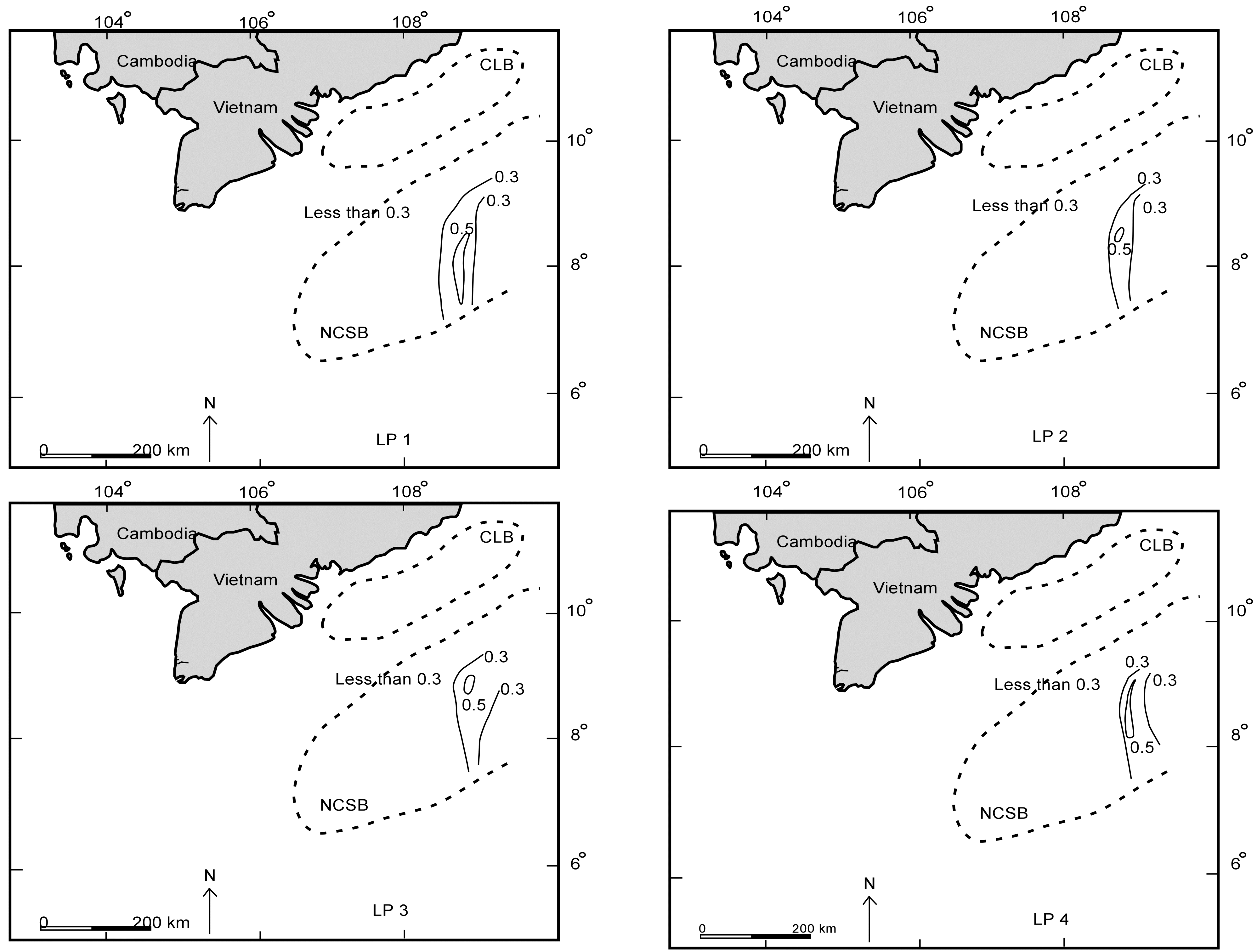

Figure (8). Isopach maps for strata of LP 1. LP 2, LP 3, and LP4. Contours are in 0.2 seconds TWT intervals. Cuu Long (CLB) and Nam Con Son Basin (NCSB) boundaries are indicated by dashed lines. Division of the Nam Con Son Basin into East and West sub-basins is not shown.

LP1 Lowstand Systems Tract: Interpretation & Description

LP1 LST strata are bounded below by SB 1 (UMU) and on the top by a transgressive surface (Figure 5). Stratal reflectors of the LST have low to medium amplitudes, medium lateral continuity, downlap onto the UMU, and exhibit progradational geometries. LP 1 LST strata reach a maximum thickness of ~0.2 seconds TWT.

Sediment bypass occurred over the Cuu Long Basin, Con Son Ridge and Western Nam Con Son Sub-Basin, allowing for deposition of lowstand strata in the eastern reaches of the study area.

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LP I Transgressive Systems Tract: Interpretation & Description

LP 1 TST strata are bounded on the bottom by a transgressive surface and on the top by a maximum flooding surface (Figure 5). Stratal reflectors of the TST have low amplitudes, medium lateral continuity, and onlap with a back-stepping geometry onto the LP 1 LST. LP 1 TST strata reach a maximum thickness no greater than 0.1 seconds TWT in the Eastern Nam Con Son Sub-Basin.

Back-stepping geometry is only present in the eastern reaches of the study area above the LP 1 LST. LP 1 TST strata thin to one reflector over the Cuu Long Basin, Con Son Ridge and Western-Nam Con Son Sub-Basin.

LP 1 Highstand Systems Tract: Interpretation & Description

LP 1 HST strata are bounded below by a maximum flooding surface and above by SB 2 (Figure 5). In the Cuu Long Basin and Western Nam Con Son Sub-Basin, LP 1

HST strata display very low-angle shingled progradational clinoforms with low to medium amplitudes and high lateral continuity. In Eastern Nam Con Son Sub-Basin HST strata are characterized by progradational clinoform-wedge facies with sigmoidal geometries and toplap truncation of the terminal clinoforms. Eastward of the clinoforming wedge facies, LP 1 HST strata become sub-parallel with low to medium amplitudes and medium lateral continuity.

Very low angle progradational clinoforms of the LP 1 HST in the Cuu Long and Western Nam Con Son Sub-Basin are indicative of progradational outer shelf facies across a low accommodation setting. Toplap truncation of the uppermost clinoform wedge strata was caused by rapid base level drop. Sub-horizontal and laterally continuous strata of the Eastern Nam Con Son Sub-Basin are indicative of slope to deep water depositional environments.

Lower Pliocene Sequence 2 (LP 2)

LP 2 (Figure 5) is defined by SB 2 at its base and SB 3 at its top. SB 3 is identified by zones of fluvial incision features that are updip of LP 3 LST, and transitions eastward into a toplap truncation surface on top of the clinoform-wedge facies of the underlying terminal LP 2 HST strata. Fluvial incisions along SB 3 are ~0.1 – 0.5 km wide and 0.05 – 0.1 seconds TWT deep. Incisions are formed within ~20 km of the updip limits of the LP 2 LST.

LP 2 is recognizable throughout the study area in both the Cuu Long and Nam Con Son Basins. In the Cuu Long Basin and over the Con Son Ridge, LP 2 is less than ~0.3 seconds TWT thick. In the Western Nam Con Son Sub-basin, LP 2 is ~0.3 – 0.35

seconds TST thick and thickens into the Eastern Nam Con Son Sub-basin where it attains its maximum thickness of ~0.5 seconds TWT within progradational clinoform facies. LP 2 thins farther eastward to less than 0.3 seconds TWT where clinoform facies transition into distal slope and basin-floor facies (Figure 8).

LP 2 Lowstand Systems Tract: Interpretation & Description

LP 2 LST strata are bounded below by SB 2 and on the top by a transgressive surface (Figure 5). Stratal reflectors of the LST have low to medium amplitudes, medium lateral continuity, downlap onto SB 2 and exhibit progradational geometries. LP 2 LST strata reach a maximum thickness of ~0.2 seconds TWT.

Sediment bypass occurred over the Cuu Long Basin, Con Son Ridge and Western Nam Con Son Sub-Basin, allowing for deposition of LP 2 LST strata in the eastern reaches of the study area.

LP 2 Transgressive Systems Tract: Interpretation & Description

LP 2 TST strata are bounded on the bottom by a transgressive surface and on the top by a maximum flooding surface (Figure 5). Stratal reflectors within the TST have low amplitudes, medium lateral continuity, and onlap onto the LP 2 LST. LP 2 TST strata are no greater than 0.1 seconds TWT thick in the Eastern Nam Con Son Sub-Basin.

Back-stepping geometries are only present in the eastern reaches of the study area above the LP 2 LST. The shallow dip and large surface area of the Sunda Shelf caused updip LP 2 TST strata to thin to one reflector over the Cuu Long Basin, Con Son Ridge and Western-Nam Con Son Sub-Basin.

LP 2 Highstand Systems Tract: Interpretation & Description

LP 2 HST strata area bounded below by a maximum flooding surface and on the top by SB 3 (Figure 5). In the Cuu Long Basin and Western Nam Con Son Sub-Basin Sequence II HST strata display very low-angle shingled progradational clinoforms with low to medium amplitudes and high lateral continuity. In Eastern Nam Con Son Sub-Basin HST strata progradational clinoform-wedge facies are formed. These reflectors exhibit sigmoidal geometries, with minor toplap truncation of the last clinoforms. Eastward of the clinoforming wedge, LP 2 HST strata become sub-parallel with low to medium amplitudes and medium lateral continuity.

Very low angle progradational clinoforms in the Cuu Long and Western Nam Con Son Sub-Basin are indicative of an inner shelf to slope settings. Toplap truncation of clinoform wedge strata was caused by rapid base-level drop. Sub-horizontal and laterally continuous strata of the Eastern Nam Con Son Sub-Basin are indicative of slope to deep water depositional environments.

Lower Pliocene Sequence 3 (LP 3)

LP 3 (Figure 5) is defined by SB 3 at its base and SB 4 at its top. SB 4 is identified by zones of fluvial incision westward of the LP 4 LST, and toplap truncation of underlying terminal LP 3 HST strata. Incisions along SB 4 are ~0.1 – 0.5 km wide and ~0.05 – 0.1 seconds TWT deep and are found within ~10 – 30 km westward of the Sequence IV LST.

LP 3 is recognizable throughout the study area in both the Cuu Long and Nam Con Son Basins. In the Cuu Long Basin, over the Con Son Ridge, and in the Western

Nam Con Son Sub-basin LP 3 is less than ~0.3 seconds TWT thick. It then thickens into the Eastern Nam Con Son Sub-basin where it attains its maximum thickness of ~0.55 seconds TWT, within progradational clinoform facies. LP 3 thins farther eastward to less than 0.3 seconds TWT where clinoform facies transition into distal slope and basin-floor facies (Figure 8).

LP 3 Lowstand Systems Tract: Interpretation & Description

LP 3 LST strata are underlain by SB 3 and on the top by a transgressive surface (Figure 5). Stratal reflectors of the LST have low to medium amplitudes, medium lateral continuity, downlap onto SB 3 and exhibit progradational geometries. LP 3 LST strata reach a maximum thickness of ~0.2 seconds TWT.

Sediment bypass occurred over the Cuu Long Basin, Con Son Ridge and Western Nam Con Son Sub-Basin, allowing for deposition of lowstand strata in the eastern reaches of the study area.

LP 3 Transgressive Systems Tract: Interpretation & Description

LP 3 TST strata are bounded below by a transgressive surface and on the top by a maximum flooding surface (Figure 5). Stratal reflectors of the TST have low amplitudes, medium lateral continuity, and onlap onto the LP 3 LST. LP 3 TST strata are less than 0.1 seconds TWT thick in the Eastern Nam Con Son Sub-Basin.

Onlapping stratal geometries in the LP 3 TST are only present in the eastern reaches of the study area above the LP 3 LST. LP 3 TST strata thin to one reflector over the Cuu Long Basin, Con Son Ridge and Western-Nam Con Son Sub-Basin.

LP 3 Highstand Systems Tract: Interpretation & Description

LP 3 HST strata are bounded below by a maximum flooding surface and above by SB 4(Figure 5). In the Cuu Long Basin and Western Nam Con Son Sub-Basin, LP 3 HST strata display very low-angle, shingled progradational clinoforms with low to medium amplitudes and high lateral continuity. In the Eastern Nam Con Son Sub-Basin, HST strata are characterized by progradational clinoform-wedge facies with sigmoidal geometries and toplap truncation of the terminal clinoforms. Eastward of the clinoforming wedge, LP 3 HST strata become sub-parallel with low to medium amplitudes and medium lateral continuity.

Very low angle progradational clinoforms of the LP 3 HST in the Cuu Long and Western Nam Con Son Sub-Basin are indicative of progradational outer shelf facies across a low accommodation setting. Toplap truncation of the uppermost clinoform wedge strata was caused by rapid base level drop. Sub-horizontal and laterally continuous strata of the Eastern Nam Con Son Sub-Basin are indicative of slope to deep water depositional environments.

Lower Pliocene Sequence 4 (LP 4)

LP 4 (Figure 5) is defined by SB 4 at its base and SB 5 (Top Early Pliocene) at its top. SB 5 is identified by zones of fluvial incision, and toplap truncation along progradational clinoform wedge facies of terminal LP 4 strata. Incisions along SB 4 are ~0.1 – 0.5 km wide and ~0.05 – 0.1 seconds TWT deep.

LP 4 is recognizable throughout the study area in both the Cuu Long and Nam Con Son Basins. In the Cuu Long Basin, over the Con Son Ridge, and into the Western

Nam Con Son Sub-basin LP 4 is less than ~0.3 seconds TWT thick, but then thickens into the Eastern Nam Con Son Sub-basin where it attains a maximum thickness of ~0.6 seconds TWT, within progradational clinoform-wedge facies. LP 4 thins farther eastward to less than 0.3 seconds TWT where clinoform-wedge facies transition into basin-floor facies.

LP 4 Lowstand Systems Tract: Interpretation & Description

LP 4 LST strata are bounded below by SB 4 and on top by a transgressive surface (Figure 5). Stratal reflectors of the LST have low to medium amplitudes, medium lateral continuity, downlap onto SB 4, and exhibit progradational geometries. A basin floor fan is present down dip of the LST clinoform wedge. Internal reflectors within the basin-floor fan display bi-directional downlap, and reach a maximum thickness of 0.15 seconds TWT at the central part of the fan. LP 4 LST clinoform wedge strata reach a maximum thickness of ~0.2 seconds TWT.

Sediment bypass occurred over the Cuu Long Basin, Con Son Ridge and Western Nam Con Son Sub-Basin, allowing for deposition of lowstand strata in the easternmost parts of the study area.

LP 4 Transgressive Systems Tract: Interpretation & Description

LP 4 TST strata are bounded below by a transgressive surface and on the top by a maximum flooding surface (Figure 5). Stratal reflectors of the TST have low amplitude, moderate lateral continuity, and onlap onto the updip parts of the LP 4 LST. LP 4 TST strata reach a maximum thickness of < 0.1 seconds TWT in the Eastern Nam Con Son

Sub-Basin and then to about one reflector over the Cuu Long Basin, Con Son Ridge, and West Nam Con Son Sub-basin.

The shallow dip, large surface area, and limited accommodation across the Sunda Shelf caused updip LP 4 TST strata to thin to one reflector.

LP 4 Highstand Systems Tract: Interpretation & Description

LP 4 HST strata area bounded below by a maximum flooding surface and on the top by SB 5 (Top Early Pliocene) (Figure 5). In the Cuu Long Basin and Western Nam Con Son Sub-Basin, LP 4 HST strata consist of very low-angle shingled progradational clinoforms with low to medium amplitudes and high lateral continuity. In the Eastern Nam Con Son Sub-Basin, HST strata consist of progradational clinoform-wedge facies with sigmooidal geometries, toplap truncation of the terminal clinoforms. Eastward of the clinoform wedge facies, LP 4 HST strata become sub-parallel with low to medium amplitudes and medium lateral continuity.

Very low angle progradational clinoforms in the Cuu Long and Western Nam Con Son Sub-Basin are indicative of a progradational outer shelf depositional environment. Toplap truncation of the uppermost clinoform wedge strata was caused by rapid base level drop. Sub-horizontal and laterally continuous strata of the Eastern Nam Con Son Sub-Basin are indicative of slope to deep water depositional environments. Slump features are found in the uppermost strata in the far eastern parts of the study area (Figure 5).

Upper Pliocene to Recent Sequences (UP-R)

Five sequence boundaries are identified in lower Pliocene to Recent strata across the study area, although facies consist entirely of inner shelf and fluvial seismic facies (Figure 5). Clinoform wedge facies are recognizable just east of the study area in other seismic profiles that are being used in other studies at Texas A&M University. Early Pliocene to Recent sequence boundaries were identified by laterally concentrated zones of fluvial incision. The high frequency Pleistocene glacio-eustatic sea-level fluctuations of Wornardt et al. (2001) are difficult to distinguish.

UP-R 1 through 5 are recognizable throughout the study area in both the Cuu Long and Nam Con Son Basins (Figure 5). In the Cuu Long Basin and over the Con Son Ridge, UP-R 1 through 5 are less than ~0.3 seconds TWT thick. In the Western Nam Con Son Sub-basin, UP-R 1 through 5 are ~0.3 – 0.5 seconds TWT thick. They then thicken into the Eastern Nam Con Son Sub-basin where they attain a thickness of ~0.9 seconds TWT (Figure 9).

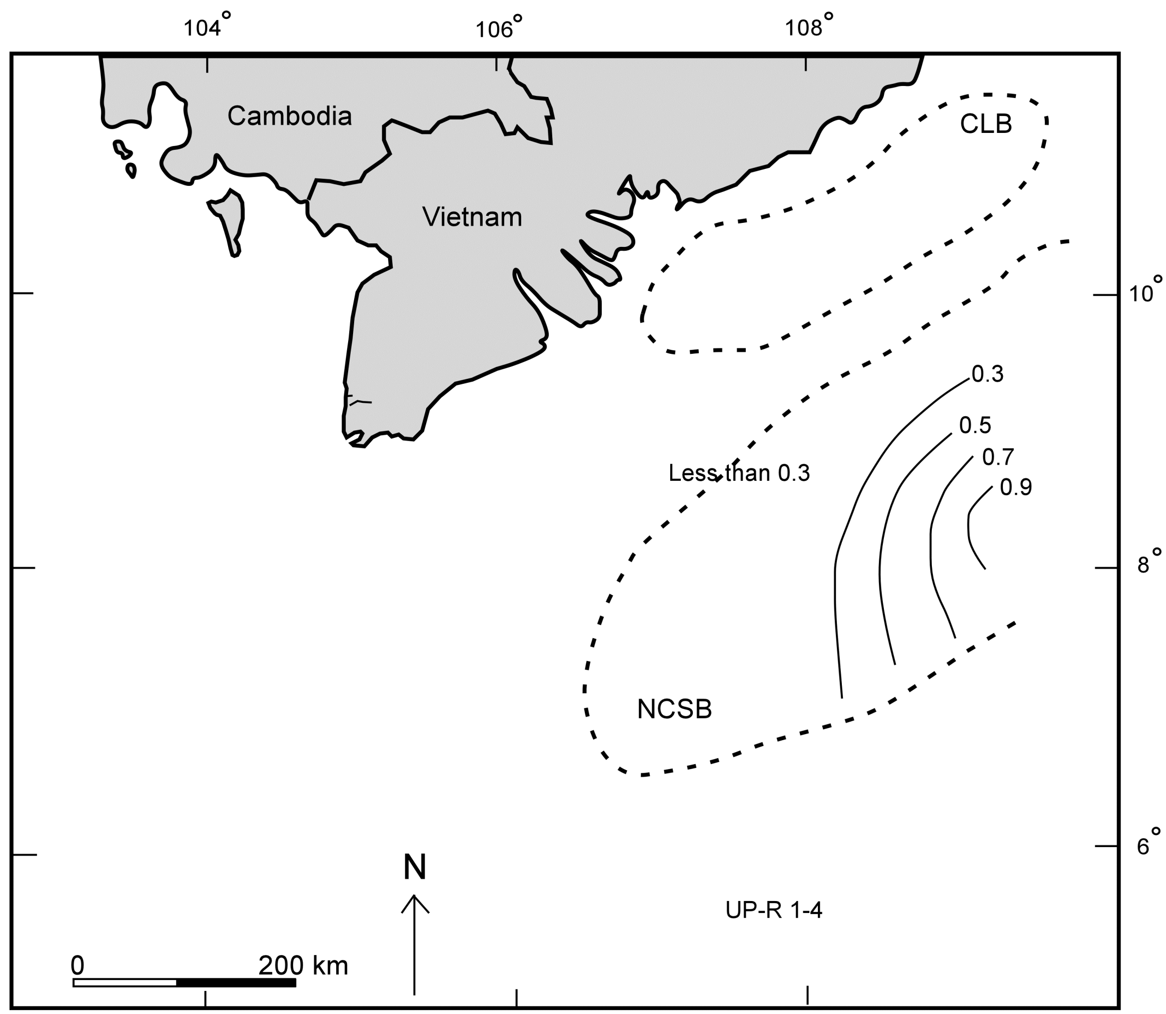

Figure (9). Combined isopach map of UP-R 1 through 4. Contour interval is in 0.2 seconds TWT. Cuu Long and Nam Con Son Basin boundaries are indicated by dashed lines. Division of the Nam Con Son Basin into East and West sub-basins is not shown.

Well Log Analysis

Well 04-A-1X (Figure 10) provided gamma-ray measurements and lithostratigraphic picks based on microfossils. Sequence boundaries for LP 1 through UP-R 4 and maximum flooding surfaces (mfs) for LP 1 through 4 were identified in the gamma-ray well log. Sequence boundary and maximum flooding surface identification was completed before comparison to the seismic data. Differential stretching of the 04-A-1X gamma-ray log (depth measured in meters) enabled correlation with the seismic data (depth measured in seconds TWT). Gamma-ray measurements were not acquired above SB 9.

Prograding packages within Pliocene strata are represented in well 04-A1-X by cleaning-upward trends in the gamma-ray log. Cleaning-upward trends are caused by a progressive upward decrease in gamma-ray values, representing a gradual increase in sand content. This gamma-ray pattern is indicative of prograding systems (Emery and Myers, 2003). Retrograding packages of Pliocene strata are represented in well 04-A-1X by dirtying-upward trends in the gamma-ray log. Dirtying-upward trends are caused by a progressive upward increase in gamma-ray values, representing a gradual increase in clay-mineral content (Emery and Myers, 2003).

Lower Pliocene Sequence 1

At the base of LP 1, the log displays a dirtying-upward trend to a strong positive gamma-ray value, which is interpreted to be the mfs. Prograding clinoforms are present in the seismic section above the mfs. The gamma-ray log displays a cleaning-upward

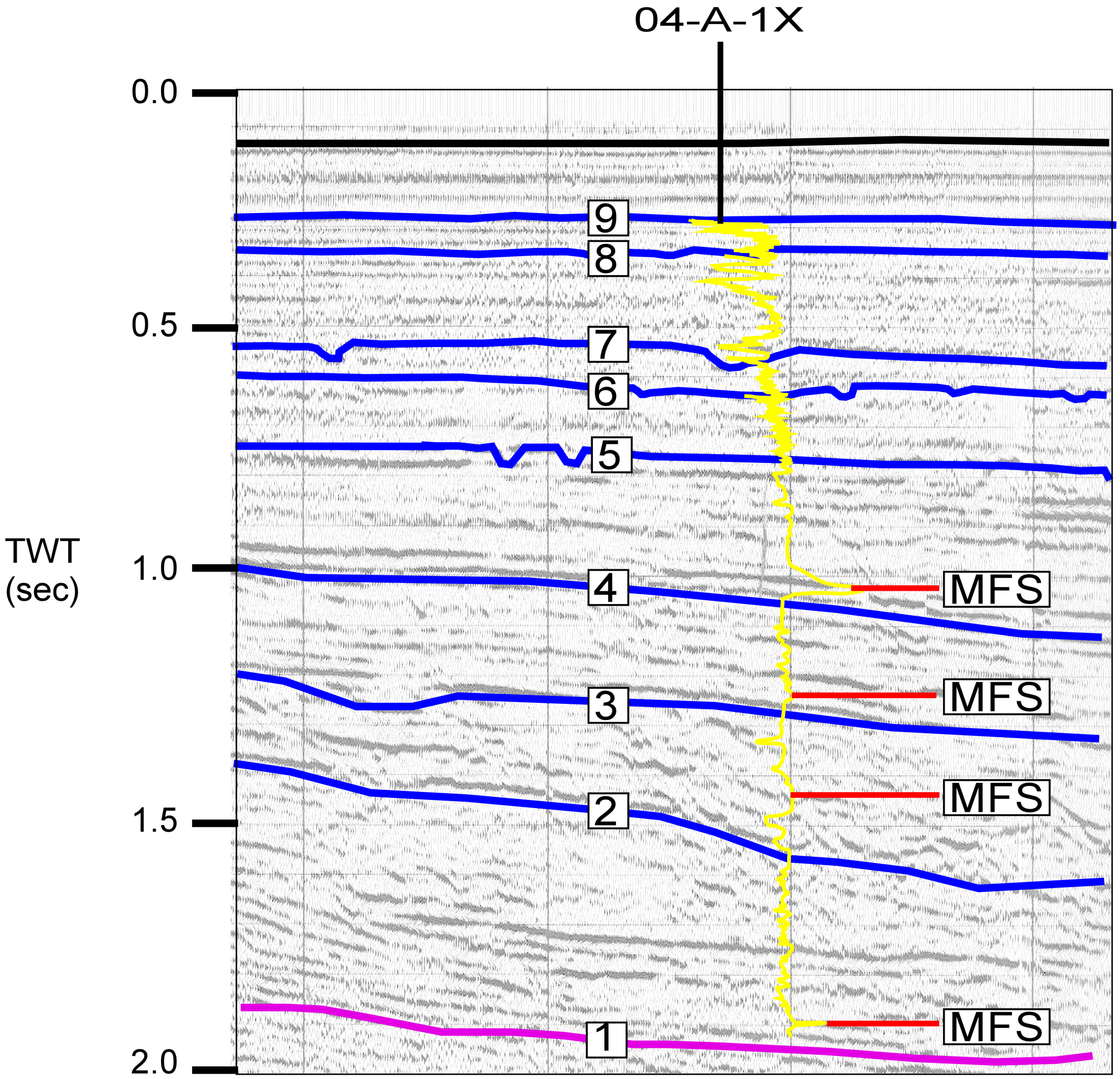

Figure (10). Enlarged view of Figure 5. Projected gamma-ray log of 04-A-1X with corresponding East Nam Con Son Sub-basin seismic section. Sequence boundaries and mfs are labeled. See Figure 5 for well location, but 04-A-1X well is located ~50 km from this seismic line.

trend above the mfs to SB 2, which reflect the progradational clinoforms of the HST.

Lower Pliocene Sequence 2

The base of LP 2 is characterized by a blocky, low gamma-ray trend, which is interpreted to be strata of the LST (Figure 10). Above the LST, the gamma-ray log displays a dirtying-upward trend to the mfs. The mfs of LP 2 does not have the same high gamma-ray value as the mfs of LP 1. Prograding clinoforms are present in the seismic section above the mfs. The gamma-ray log displays a cleaning-upward trend above the mfs to SB 3, which correspond to progradational clinoforms of the HST.

Lower Pliocene Sequence 3

Above SB 3, the gamma-ray log of the TST of LP 3 displays a dirtying-upward trend to the mfs (Figure 10). The mfs of LP 3 does not have a strong positive value like the mfs of LP 1. Prograding clinoforms are present in the seismic section above the mfs. The gamma-ray log displays a cleaning-upward trend above the mfs up to SB 4, which correspond to progradational clinoforms of the HST.

Lower Pliocene Sequence 4

Above SB 4, the log displays a dirtying-upward trend to a strong positive gamma-ray value interpreted to be the mfs of LP 4 (Figure 10). Prograding clinoforms are present in the seismic section above the mfs. The gamma-ray log displays a cleaning-upward trend above the mfs to SB 5, which reflects the progradational clinoforms of the HST.

Upper Pliocene to Recent Sequences 1 through 4

Sequence boundaries for UP-R 1 through 4 were identified on the gamma-ray log at the base of each cleaning-upward package (Figure 10). Gamma-ray readings beginning at SB 5 display higher sand composition upsection. This is likely due to increasing influence of glacio-eustatic sea-level fluctuations across the broad, relatively flat Sunda Shelf during late Pliocene to Recent time. The gamma-ray log of well 04-A-1X was no longer recorded above SB 9.

CHAPTER V

DISCUSSION

Comparison to Eustatic Sea-level Data

Wornardt et al. (2001) created a late Miocene to Recent eustatic sequence cycle chart relying on the compiled data of Hardenbol et al. (1995), and Berggren et al. (1995) with some modifications (Figure 11). Wornardt et al. (2001) place the UMU (SB 1) event at 5.73 Ma and top of the early Pliocene (SB 5) at 3.95 Ma. Sequence boundaries 2, 3, and 4 lie stratigraphically between these two key sequence boundaries. Age determination for sequence boundaries younger than SB 5 is difficult due to lack of well control and shallow seismic resolution.

Sediment Thickness Patterns

Seismic stratigraphic analysis indicates that fluvial to shelf-edge facies of the study area migrated east to southeast during Pliocene to Recent time. The east to southeast progradation direction of clinoform facies indicates the Paleo-Mekong River System has been the dominant sediment source for the area during Pliocene to Recent time. The modern shelf-edge clinoform complex has migrated just east of the limits of the seismic data used during this study, although other work in progress at Texas A&M University covers the modern shelf edge.

During early Pliocene time, fluvial incision occurred across shelf areas during base level falls. Fluvial influence is most prominent in upper Pliocene to Recent strata,

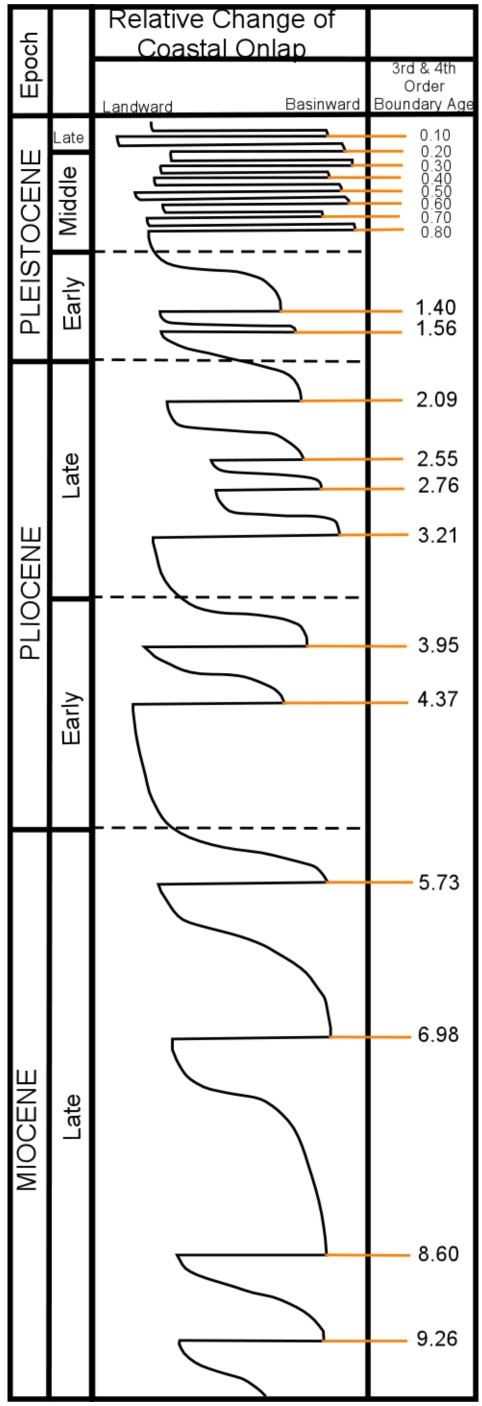

Figure (11). Late Miocene to Recent eustatic sea-level curve (modified from Wornardt et al., 2001).

which likely reflects increasing influence of higher amplitude third-order eustatic sea-level fluctuations.

No major tectonic deformation or differential subsidence influenced stratal architecture of the Pliocene to Recent strata of the study area. Isopach maps of Sequences LP 1 through UP-R 5 suggest areas of greatest tectonic subsidence occurred in the Eastern Nam Con Son Sub-basin. Greater tectonic accommodation space in the Eastern Nam Con Son Sub-basin allowed for the Paleo-Mekong River System to deposit extensive shelf-edge complexes during Pliocene to Recent time.

CHAPTER VI

CONCLUSIONS

Sequence stratigraphic analysis of the 1989 HGS survey enabled identification of transitions from fluvial-deltaic to deep-marine sediment depositional facies across offshore Vietnam during Pliocene to Recent time. Regionally, the entire Pliocene to Recent succession records progressive east to southeastward progradation from the Cuu Long to Eastern Nam Con Son Sub-basin.

The main conclusions from this study are:

1) Seismic stratigraphic analysis of the Pliocene to Recent section of the study area identified at least nine sequences and their accompanying systems tracts.
2) Pliocene to Recent strata of the Cuu Long Basin, Con Son Ridge, and Western Nam Con Son Sub-basin are dominated by horizontal to very low-angle, parallel to sub-parallel reflectors and no areas of shelf-edge development. Pliocene to Recent shelf-edge development in the study area is limited to the Eastern Nam Con Son Sub-Basin.
3) Pliocene to Recent lowstand fluvial incision is most prevalent in the Eastern Nam Con Son Sub-Basin, concentrated in the eastern reaches of the study area. Fluvial incision is more dominant in upper Pliocene to Recent strata. This is likely due to increasing influence of glacio-eustatic sea-level fluctuations across the broad, relatively flat Sunda Shelf during late Pliocene to Recent time.

4) Since early Pliocene time, the shelf-edge complex has moved east to southeast in the Eastern Nam Con Son Sub-basin. The late Pliocene to Recent shelf-edge complex is located just east of the study area.
5) South to southeastward migration of the shelf edge complex during Pliocene to Recent time indicates that the Paleo-Mekong River System was the dominant sediment source for the area.

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VITA

Name: Christopher Neil Yarbrough

Address: Dominion Exploration & Production, Inc.
1415 Louisiana
Suite 2700
Houston, TX 77002

Email Address: Christopher_N_Yarbrough@dom.com

Education: B.S., Geology, Texas A&M University, 2002
M.S., Geology, Texas A&M University, 2006